

COMPUTER-ASSISTED AND IMAGE-GUIDED ABDOMINAL INTERVENTIONS

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ABSTRACT

This paper gives an overview of computer-assisted and image-guided systems for abdominal interventions. Computer-assisted means that the power of the computer is used to provide the physician a virtual reality view of the anatomy. Image-guided means that the intervention is carried out based on imaging modalities such as CT, MRI, and ultrasound. These minimally invasive procedures are rapidly increasing in popularity as they cause less trauma to the patient and the technology to carry them out continues to improve.

Index Terms— computer-assisted, image-guided, abdominal interventions, electromagnetic tracking

1. INTRODUCTION

While most computer-assisted and image-guided systems to date have been based on optical tracking, the line of sight limitation of this tracking technique makes it unsuitable for tracking inside the body. Therefore, the systems described in this paper are based on electromagnetic tracking, which is not as accurate as optical tracking, but is capable of tracking inside the body. In fact, the recent improvement and miniaturization of electromagnetic tracking systems has enabled the development of most of the systems presented here. It should be noted that many of these systems have been developed for research purposes to date, and that there are only a few FDA approved systems for abdominal interventions at the time of this writing.

This paper describes the efforts of various researchers for procedures in the lung and liver. We have attempted to include the major studies as listed in Table 1. Note that most of this work is relatively recent, beginning with the work of Solomon et al. in the late 1990s. The remainder of this paper describes these efforts, using Table 1 as a guide. This paper is part of a chapter on abdominal interventions from a forthcoming book on image-guided interventions [1].

2. LUNG: BRONCHOSCOPIC BIOPSY

Bronchoscopy is the examination of the airways with an optical camera mounted on a rigid or flexible guide. It is used to evaluate the endobronchial structures and mucosa and can be used as both a diagnostic and a therapeutic tool.

Bronchoscopy is frequently done using a flexible bronchoscope with a mounted fiberoptic camera. The bronchoscope also has a working channel through which instruments may be used to take tissue samples or provide therapy. An illustration of bronchoscopy is shown in Figure 1. Several researchers have investigated image-guided systems for bronchoscopy and one commercial system is available as described next.

Organ	Procedure	Tracking System	Trial	Modality	Reference
Lung	Bronchoscopic biopsy	Biosense	8 Swine, 15 Humans	CT	[2, 3]
		Super-Dimension	4 Swine, 13 Humans, 30 Humans	CT	[4-6]
Liver/Abdomen	TIPS	Biosense	5 Swine	CT	[7]
		Aurora	Swine	CT	[8]
	Biopsy	Aurora	Phantoms, 3 Swine	CT	[9, 10]
		UltraGuide	43 Humans	US	[11]
		UltraGuide	39 Humans	US	[12]

Table 1. Representative abdominal interventions

2.1. Early work

The integration of electromagnetic tracking with pre-procedure CT for navigation in bronchoscopy was first reported by Solomon et al. [2]. This work was based on the Biosense system and used a 1.5 mm diameter six degree of freedom position sensor which was placed at the tip of a flexible bronchoscope. The Biosense system uses three external electromagnetic emitters that can track within an approximately 20 by 20 by 20 cm region.

Two studies were completed by Solomon: the first study [2] was in eight swine and the second study [3] was in fifteen humans. The swine study used 35 kg animals. Synthetic paratracheal lesions approximately 2 cm in diameter were created to serve as targets using a mixture of radiographic contrast and tissue adhesive. Next, 10-20 metallic nipple markers of 1 cm diameter were secured on the anterior chest wall for use in registration. The images of the swine thorax were acquired on a CT scanner after administration of intravenous contrast and the images were reconstructed with 2 mm spacing. End-expiration breath hold was achieved during scanning by turning off the

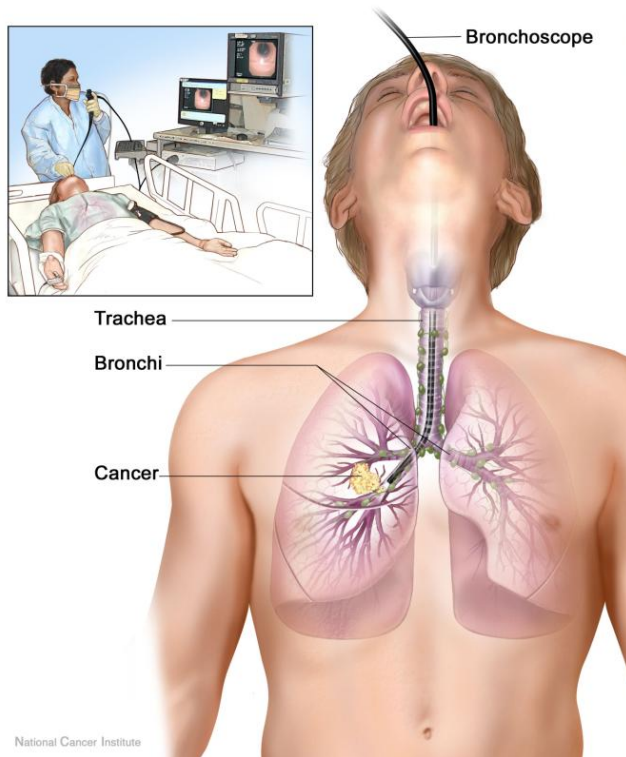


Figure 1. Bronchoscopy

(public domain image from U.S. National Cancer Institute)

ventilator during the scan while the swine were paralyzed with pancuronium.

Solomon and colleagues then extended their work in this area by conducting a clinical trial in 15 patients [3]. They compared two registration techniques to assess if there were any differences between skin fiducial-based registration and endotracheal anatomy-based registration.

They achieved a registration error of 5.6 ± 2.7 mm using the skin fiducial method. They were unable to measure the registration error of the second method, but subjectively judged it to be more accurate, based on the fiberoptic view of the endobronchial tree. The disadvantage of the second method was that it took more bronchoscopy time as the registration was done during the bronchoscopy session.

2.2. Clinical evolution

Bronchoscopy is one abdominal procedure where an FDA-approved system exists, called Bronchus from super-Dimension Ltd (Hertziya, Israel). The system was approved in November 2005 for guiding endoscopic instruments in the pulmonary tract. The system consists of a tracking device, tracked instruments, and computer-based display.

The tracking system is proprietary and based on a 1 cm thick and 47 cm by 56 cm wide localization board that is placed underneath the patient [5]. The board emits low-frequency electromagnetic waves that are detected by a sensor probe of 1 mm diameter by 8 mm in length. This probe is incorporated into the tip of a flexible catheter 130

cm in length and 1.9 mm in diameter, which can be inserted into the working channel of the bronchoscope. The registration technique is based on anatomic landmarks and the system does not use artificially placed fiducials.

In their initial animal studies Schwarz et al. achieved a 4.5 ± 2.5 mm fiducial target registration error in four animals with a total of ten artificially created lesions [5]. This same group then completed a clinical trial in 30 patients with peripheral lung lesions (mean distance to pleura 1.9 mm) and reported a 69% diagnostic biopsy yield [4]. They used a registration technique based on touching anatomic landmarks such as the main carina or the left, right, or middle lobe carina. An average target registration error of 6.12 ± 1.7 mm was achieved. In a related study with 15 patients using this system, 9 diagnostic transbronchial biopsies were achieved [5]. The authors also reported a false negative biopsy in 4 patients in this cohort. A diagnostic biopsy for these patients was then achieved by conventional CT-guided fine needle aspiration or surgery.

3. LIVER

The liver, much like the lung, is subject to considerable respiratory motion. The predominant motion is cranio-caudal due to respiratory excursion of the diaphragm [13]. Therefore, the targeting of the internal structures of the liver, such as the vasculature and the bile ducts might be made easier using image guidance. Specifically, the creation of a transjugular intrahepatic portosystemic shunt (TIPS), as is frequently done in the setting of acute gastric variceal hemorrhage, was attempted with electromagnetic guidance. The biopsy of intrahepatic targets was also investigated, and these topics are described in this section.

3.1. Transjugular intrahepatic shunt placement (TIPS)

TIPS is a fluoroscopically-guided procedure performed by interventional radiologists. The procedure is performed in patients with acute gastric or esophageal bleeding which can be life threatening. The goal of the procedure is to create an intrahepatic connection (shunt) between the portal venous system and the hepatic venous system. The procedure is considered technically challenging and is even more difficult in emergency settings.

The first paper in this area was by Solomon et al. [7] and investigated the use of the Biosense electromagnetic navigation system for this procedure. A 16-gauge, 50 cm curved needle was used to create a connection between the hepatic vein and the portal vein. Prior to CT scanning, five domestic swine had 10-20 one mm metallic nipple markers placed on the abdominal wall to allow for later image registration. The swine were scanned with spiral CT using intravenous contrast and the images were reconstructed with 2 mm spacing. End-expiration breath hold was achieved by turning off the ventilator during the scan while the swine were paralyzed with pancuronium.

The position sensor was passed through the long curved needle to provide the position and orientation of the needle

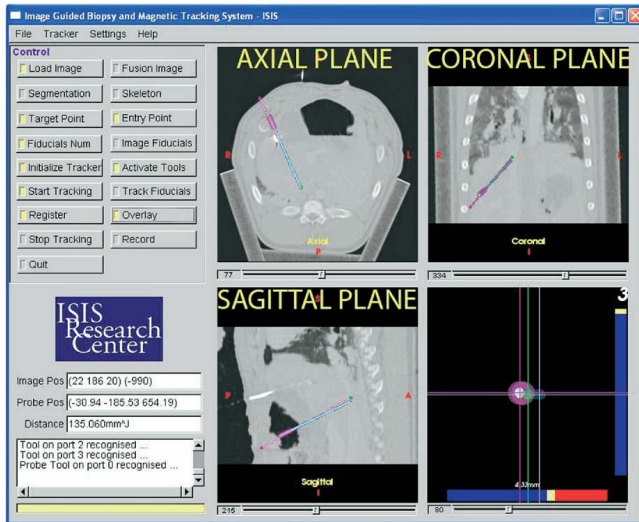


Figure 2. Graphical User Interface
(Reprinted with permission from [8])

tip. An additional position sensor was placed on the swine's abdomen and used to monitor respiratory motion. The position of the needle tip was updated on the monitor when the swine was within a 1 mm threshold of end expiration. During the procedure, image registration was performed by touching eight nipple markers with the position sensor. The accuracy of the system was then estimated by touching the other 12 nipple markers and comparing the perceived location of them on the CT scan with the actual location. The average difference found was 3 mm. Multi-planar reconstructed images were then used along with tracking of the needle tip to access the portal vein.

Successful TIPS formation was performed in four out of five animals and the one failure was attributed to a dull needle. The system was found to be useful for providing a better visualization of the anatomy and needle tip localization during the procedure.

More recently, Levy and colleagues used an Aurora-based navigation system to create a modified version of the TIPS procedure in swine [8]. Using four skin fiducials and four active needle based fiducials, this group created a successful transhepatic puncture using electromagnetic guidance. This was done by puncturing the portal vein, hepatic vein, and inferior vena cava in a single percutaneous transabdominal puncture followed by placement of an intrahepatic stent.

The graphical user interface and needle targeting window is shown in Figure 2. Needle advancement was performed only when the GUI indicated that respiratory-related organ motion had ceased during the typically observed approximately 1.4 second regular end-expiratory phase pause. The system tracks the motion of an electromagnetically tracked internal fiducial to determine the timing of the pause in respiratory-related organ motion and indirectly the optimal target position. The GUI displays (a) the depth of the needle tip relative to the target depth in

graphical fashion and (b) the position of the needle tip registered with the preoperative CT data set. The needle procedure can therefore be terminated by the operator based on the real-time information and guidance provided by the GUI.

3.2. Biopsy and thermoablation

Our research group at Georgetown has been focusing on electromagnetic tracking for delivery of instruments into small liver targets to enable more precise biopsies. We developed an image-guided system based on the Aurora electromagnetic tracking device. Initially, image-guided biopsy of synthetic liver lesions and small nodules in phantoms and anesthetized swine was performed in an angiography suite [9].

The mean RMS error of needle placement was 6.4 mm in the phantom, and 8.3 mm in the swine. However, the system enabled less experienced operators to perform as well as fellowship trained interventional radiologists in terms of procedure time and accuracy of needle probe delivery.

Some systems improvements were then made and biopsy needle insertion was carried out in the CT-fluoroscopy suite [10]. We demonstrated in swine that using electromagnetic tracking and image guidance alone one can achieve at least equivalent accuracy as with CT-fluoroscopy guided needle insertion (Figure 3). There was a trend towards improved accuracy with electromagnetic tracking and image guidance, but the results were not statistically significant. In addition, radiation dose and total time of needle manipulation was significantly reduced using our system.

In parallel with our efforts, Wood et al. also used the Aurora system to show the feasibility of in vivo tracking on a catheter and needle based systems using co-registration with multiple modalities such as CT, MRI, and PET [14, 15]. These studies demonstrated the versatility of electromagnetic tracking as an adjunctive guidance modality across the spectrum of imaging methods used for imaging and intervention.

An early clinical system incorporating electromagnetic tracking was the Ultraguide 1000 (UltraGuide Ltd., Tirat Hacarmel, Israel). The Ultraguide system consisted of a computer, monitor, and a proprietary electromagnetic tracking system. All components were mounted on a movable trolley including the magnetic field generating coils of the tracking system. A magnetic field sensor was then attached to the transducer and a second field sensor was attached to the hub of the needle. The navigation volume is a 50 cm cube.

Howard et al. [11] showed the clinical utility of this system in a 43 patient study which included a biopsy of solid organs in 24 patients including 14 livers. They formulated a subjective scoring system of physician's impressions while using the device, and concluded that the system would be beneficial as an adjunctive technology in approximately half of the ultrasound-guided procedures in their practice.

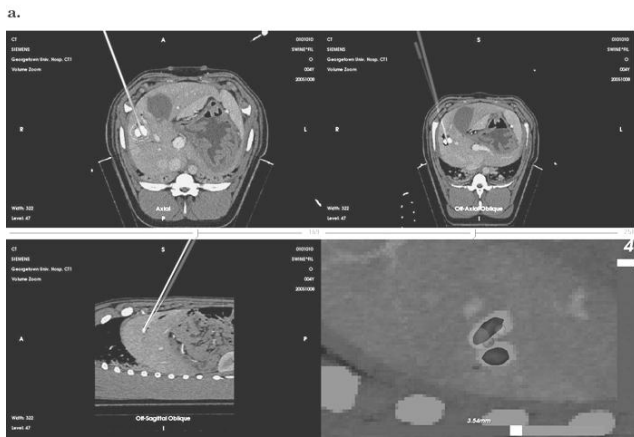


Figure 3. Swine study for biopsy in CT suite
(Reprinted with permission from [10])

In related work, Birth et al. [12] performed 39 interventional procedures under OR conditions using an improved system called the Ultraguide 2000. Twenty three of these procedures were thermal ablations of the liver malignancies, and 16 were diagnostic biopsies. The authors reported technical success with out-of-plane probe insertion in all cases and reported no complications. They concluded that the system increases the safety of the procedures, particularly when lesions are difficult to reach or next to critical structures.

4. SUMMARY & FUTURE DIRECTIONS

In summary, the use of electromagnetic tracking and image guidance in abdominal applications is still evolving, and preclinical studies in swine and early clinical studies with humans have shown promise. The inherent error introduced by motion and deformation is still a major roadblock in accurate registration and will continue to be a topic of research. However, electromagnetic tracking has improved where it can be used reliably in clinical environments such as the interventional suite where metallic and electromagnetic interference is minimal. Clinicians and

scientists need to work together to develop the next generation of these systems for improved patient care.

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